

Energy efficiency and economic feasibility of CCHP driven by stirling engine

X.Q. Kong, R.Z. Wang ^{*}, X.H. Huang

*Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University,
1954 Huashan Road, Shanghai 200030, PR China*

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Abstract

This paper deals with the problem of energy efficiency evaluation and economic feasibility analysis of a small scale trigeneration system for combined cooling, heating and power generation (CCHP) with an available Stirling engine. Trigeneration systems have a large potential of energy saving and economical efficiency. The decisive values for energetic efficiency evaluation of such systems are the primary energy rate and comparative primary energy saving (Δq), while the economic feasibility analysis of such systems relates the avoided cost, the total annual saving and payback period. The investigation calculates and compares the energy saving and economic efficiency of trigeneration system with Stirling engine against contemporary conventional independent cooling, heating and power, showing that a CCHP system saves fuel resources and has the assurance of economic benefits.

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Keywords: Combined cooling, heating and power; Stirling engine; Energy efficiency; Economic analysis

1. Introduction

Trigeneration is the concept of deriving three different forms of energy from the primary energy source, namely cooling, heating and power generation. Also referred to as combined cooling, heating and power generation (CCHP), this option uses absorption technology to supply heating and cooling to an application in combined heating and power (CHP) systems.

A CHP system simultaneously produces and uses heat and power, which reduces the primary energy consumption, compared to independent generation of the heat and power, due to the

^{*} Corresponding author. Tel.: +86-21-6293-3250; fax: +86-21-6293-2601.

E-mail address: rzwang@mail.sjtu.edu.cn (R.Z. Wang).

Nomenclature

COP	coefficient of performance (dimensionless)
Q_{pc}	primary energy demand of CCHP system (kW)
Q_{ps}	primary energy demand of conventional independent system (kW)
Q	heat flow rate, extracted or supplied (kW)
P	electrical output (kW)
Q_c	refrigerating output (kW)
Q_h	heating capacity (kW)
Q'_{hw}	domestic hot water heating capacity supplied by absorption chiller (kW)
Q''_{hw}	domestic hot water heating capacity supplied by heat exchanger (kW)
$\sum Q_h$	sum of utilized heat output of CCHP system (kW)
$\sum Q_c$	sum of utilized cooling capacity of CCHP system (kW)
$\sum P_c$	sum of utilized power output of CCHP system (kW)
$\sum Q_{hw}$	sum of utilized domestic hot water heating capacity of CCHP system (kW)
η_b	boiler efficiency (dimensionless)
η_e	generating efficiency of thermal power station (dimensionless)
Δq	comparative saving of primary energy demand (dimensionless)
PER	primary energy rate (dimensionless)
CC	capital costs (RMB¥)
AC	avoided cost (RMB¥)
AS	total annual saving (RMB¥)
PP	payback period (year)
HP	heat price (RMB¥/MW h)
CP	cold price (RMB¥/MW h)
HWP	domestic hot water price (RMB¥/t)
EP	electricity price (RMB¥/kW h)
NGP	natural gas price (RMB¥/N m ³)
$\sum$ NGBC	annual natural gas burning capacity (N m ³ /y)
MC	maintenance cost (RMB¥)
RC	running cost (RMB¥)

Subscripts and abbreviations

CCHP	combined cooling, heating and power generation
c	CCHP system
s	conventional independent cooling, heating and power system
ST	Stirling engine
g	exhaust gas of Stirling engine
w	cooling water of Stirling engine's cylinders
hw	domestic hot water
cr	compression refrigeration plant

utility of the exhaust heat [1–4]. Hendriks and Blok [5] discussed that the savings in primary energy by small scale CHP gas turbine units can be about 30% when power generation replaces conventional power and about 15% when power generation replaces natural gas fired combined cycles. In most applications, the main factor that determines a high energy and economic efficiency of the CHP scheme is a high utilization of the heat and power that are produced simultaneously. The British Energy Efficiency Office has recommended that the system should run for a minimum of 4500 h per annum [6,7]. As a result, this requires that in most practical applications of the CHP system, the need for both heat and electric power must be balanced throughout the year. The main difficulty in achieving high annual utilization is providing a heat demand during the summer months. A summer demand for the heat generated by a CHP system can be provided if the system uses absorption technology. A typical CCHP facility consists of a cogeneration plant and an absorption chiller that produces cooling or heating by making use of some heat recovered from the CHP system.

Until recently, this option has been limited to companies requiring large amounts of energy, 1 MW or greater. The US Department of Energy (DOE) has recently introduced a new initiative that includes space cooling in the useful energy outputs of combined energy systems and has designated this as Buildings Cooling, Heating and Power “BCHP” [8]. The present study investigates a small scale CCHP system with an available Stirling engine and a double effect absorption chiller.

The Stirling engine is an external combustion engine, which is the mechanical device working theoretically on the Stirling cycle, or its modification. The cycle provides a constant volume process during the transfer of working fluid between the hot and cold spaces of the engine and provides a constant temperature heating and cooling process during compression and expansion. The compression and expansion processes of the cycle generally take place in a cylinder with a piston. Since the combustion of the Stirling engine is a continuous process, it can burn fuel more completely and is able to use all kinds of fuel with any quality. It offers the possibility for having a high efficiency engine with less exhaust emissions in comparison with the internal combustion engine. What’s more, its reliability is high, and its costs are low. Stirling engines are simple and safe to operate, run almost silently on any combustible fuel and are clean and efficient compared to steam engines [9–11]. Table 1 offers a comparison of the technical and economical parameters distinguishing CCHP technologies.

Table 1
Technical and economical parameters distinguishing CCHP technologies

Parameters	Units	Stirling engine	Micro-turbine	Internal combustion engine
Capacity	kW	25–100	25–100	25–5000
Electric efficiency	%	29–40	25–30	25–45
Noise (distance of 3 feet)	dBA	50–75	57–82	>100
NO _x emissions	Ibs/MW h	0.4–2.0	0.4–2.2	2.2–28
Operations and maintenance	\$/kW h	0.004–0.015	0.002–0.01	0.007–0.015

Source: ONSITE SYCOM Energy Corporation, 1999 (except for Stirling Engine data).

The absorption refrigeration system needs a heat source as the driving force, which can be supplied by the exhaust heat from CHP systems. Therefore, absorption chillers have the capability of integrating with cogeneration systems and have recently gained widespread acceptance [12,13].

2. Principles of CCHP with an available Stirling engine function and design

The principle of the CCHP system is the interconnection of the working parts of the CHP system and absorption refrigeration system. The cogeneration plant is interconnected with the generator of the absorption system directly or by a heat exchanger. Then, the generator absorbs part or all of the exhaust heat from the cogeneration plant as its driving force. Hence, with the help of one heat driven engine, the CCHP system can generate cooling, heating and electricity. Note that the absorption refrigeration cycle in the CCHP system is being practically applied mostly as a water chilling and heating unit.

There are several possible setups of the individual components of CCHP systems using a Stirling engine to obtain different ratios of the separate produced energy flows. As an example, there is an energy scheme of the CCHP system with an available Stirling engine described in Fig. 1. In the figure, the CCHP system consists of a Stirling engine with natural gas as the primary energy demand Q_{pc} and of a generator for power production with an absorption refrigeration system that works also as a water chilling and heating unit. The electrical output P_c of the CCHP system is available as a utility energy flow. The heating capacity of the Stirling engine Q_{ST} is given by the total of the heating output Q_g from combustion products and the heating output Q_w from cooling the cylinders ($Q_{ST} = Q_g + Q_w$).

The CCHP system described in Fig. 1 uses the exhaust heat Q_g from the combustion products to supply the thermal energy demand for the absorption refrigeration system. Heat flow Q_w from the Stirling engine cylinder cooling is used for water heating. The cooling tower performs the cooling of the absorber and condenser of the absorption refrigeration system. The system in Fig. 1 will produce the refrigerating output Q_c from the evaporator of the absorption refrigeration system in the summer and the heating output Q_h from the generator of the absorption refrige-

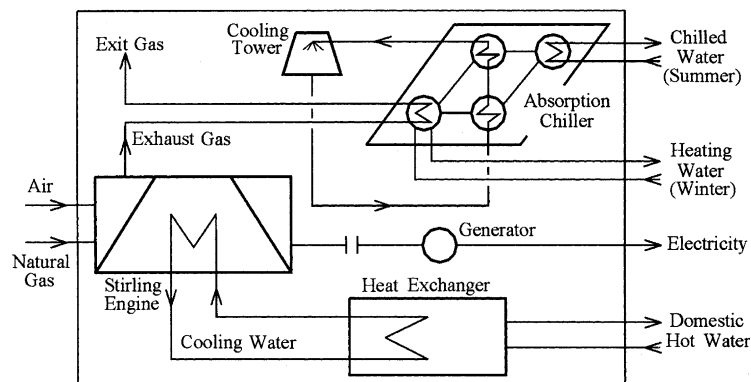


Fig. 1. Schematic diagram of the CCHP system with utilization of exhausted heat from Stirling engine combustion gases as a driving heat source for absorption refrigeration system.

ration system in the winter. In the spring and autumn, the generator supplies heat for domestic hot water heating Q'_{hw} . At the same time, the domestic hot water heating output Q''_{hw} is obtained from the heat exchanger all year round.

3. Evaluation and calculation of designed CCHP energy efficiency

The well known evaluation of the energy efficiency of systems for heating and cooling production by means of the value of coefficient of performance (COP) is not a satisfactory criterion for the proposed trigeneration systems compared with conventional independent cooling, heating and power generation. The decisive value for the energy efficiency evaluation of such energy cycles is the primary energy rate (PER). The PER is the ratio of primary energy demand to the required output, and consequently, the system with the lowest value of PER is considered the best with regard to energy consumption [14–17]. The PER values for the designed CCHP and independent production of the individual energy flows can be expressed on the basis of the given PER definition.

The PER value for the CCHP can be expressed by the following equation:

$$PER_c = \frac{Q_{pc}}{\sum Q_h + \sum Q_c + \sum Q_{hw} + \sum P_c} \quad (1)$$

The values of $\sum Q_h$, $\sum Q_c$, $\sum Q_{hw}$ and $\sum P_c$ can be expressed in the following forms:

$$\text{In summer : } \sum Q_h = 0 \quad \sum Q_c = Q_c \quad \sum Q_{hw} = Q''_{hw} \quad \sum P_c = P_c \quad (2)$$

$$\text{In winter : } \sum Q_h = Q_h \quad \sum Q_c = 0 \quad \sum Q_{hw} = Q''_{hw} \quad \sum P_c = P_c \quad (3)$$

$$\text{In spring and autumn : } \sum Q_h = 0 \quad \sum Q_c = 0 \quad \sum Q_{hw} = Q''_{hw} + Q'_{hw} \quad \sum P_c = P_c \quad (4)$$

The PER value for the independent system can be expressed by the following equation:

$$PER_s = \frac{Q_{ps}}{\sum Q_h + \sum Q_c + \sum Q_{hw} + \sum P_c} \quad (5)$$

On the basis of the heating efficiency of a boiler η_b , the COP_{cr} of the vapor compression refrigeration plant and the generating efficiency of a thermal power station η_e , the primary energy demand of the conventional independent cooling, heating and power Q_{ps} can be expressed by the following equation:

$$Q_{ps} = \frac{\sum Q_h + \sum Q_{hw}}{\eta_b} + \frac{\sum Q_c}{COP_{cr} \cdot \eta_e} + \frac{\sum P_c}{\eta_e} \quad (6)$$

The comparative saving of primary energy demand Δq is defined as the ratio of the saved primary energy in the CCHP system to the primary energy consumption Q_{ps} for the conventional independent generation of the required energy flows by the equation [15]:

$$\Delta q = \frac{Q_{ps} - Q_{pc}}{Q_{ps}} \quad (7)$$

Table 2

Technical parameters of the CCHP facility and reference energy parameters

Description	Nomenclature	Units	Values
Primary energy demand of CCHP (by natural gas)	Q_{pc}	kW	220
Heating capacity of the Stirling engine	Q_{ST}	kW	146
Electrical output of CCHP	P_c	kW	50
Temperature of exhaust gas of Stirling engine	T_g	°C	675
Heating output from exhaust gas of Stirling engine	Q_g	kW	46
Outlet/inlet temperature of cooling water of Stirling engine cylinders	T_{co}/T_{ci}	°C	57/50
Heating output from cooling water of Stirling engine cylinders	Q_w	kW	100
Cooling/heating capacity of absorption chiller	Q_{ac}/Q_{ah}	kW	70/70
Chilled water outlet/inlet temperature of absorption chiller	T_{aco}/T_{aci}	°C	7/14
Heating water outlet/inlet temperature of absorption chiller	T_{aho}/T_{ahi}	°C	57/50
Temperature of domestic hot water	T_{hw}	°C	50
COP of refrigeration/heating cycle of double effect absorption chiller	COP_{ac}/COP_{ah}		1.2/0.9
Generating efficiency of a thermal power station	η_e		0.3
Heating efficiency of a boiler	η_b		0.85
COP of vapor compression air-conditioning system (room air conditioner)	COP_{cr}		2.5
COP of vapor compression refrigeration plant (central air-conditioning system)	COP_{cr}		4.5

Calculations of values of PER_c , PER_s and Δq were performed for the technical parameters of an available Stirling engine and a double effect absorption chiller (made in China), that are arranged in the CCHP system according to Fig. 1. The reference energy parameters η_b , η_e and COP_c of the conventional independent production of the demand energy flows were stated for the conditions of such system application in China. These parameters are shown in Table 2, while the results of the calculation are detailed in Table 3. The CCHP system has been running through the day all year round. The refrigeration time in summer is 3672 h (from May 15 to October 15), and the heating time in winter is 2640 h (from November 20 to March 10) during one year.

Table 3

Values of PER of CCHP and conventional independent production in summer, winter and a whole year

	In summer	In winter	In spring and autumn	In a whole year
PER of the CCHP system	1.072	1.149	1.149	1.116
PER of the conventional independent system with domestic air-conditioning system	1.745	1.74	1.74	1.742
PER of the conventional independent system with central air-conditioning system	1.585	1.74	1.74	1.672
The comparative saving of primary energy demand Δq of CCHP compared to room air conditioner	0.386	0.34	0.34	0.359
The comparative saving of primary energy demand Δq of CCHP compared to central air-conditioning system	0.324	0.34	0.34	0.333

Two conclusions can be drawn from Table 3. The first is that the PER of the CCHP system is lower than that of the conventional independent system. The comparative saving of primary energy demand Δq of the CCHP system by Eq. (7) is an average of 0.36 and 0.33, compared to the room air conditioner and central air conditioning system, respectively. This is because the CCHP system captures and uses the thermal energy produced as a by-product from fuel sources such as natural gas to increase the energy utilization rate. The second is that for the CCHP system, the PER in summer is lower than that in winter. The reason is that during the summer months, the absorption chiller is used to supply cold by the refrigeration cycle with the COP of 1.2, while it is used to supply heat by the heating cycle with the COP of 0.9 in the winter. This means that the absorption chiller is vital in ensuring the CCHP system's energy efficiency.

4. Economic analysis

The fuel savings and economics of CCHP are grounded in the laws of thermodynamics, which state that a heat source at an elevated temperature has a greater capability to perform work than the same amount of heat at a lower temperature [18]. The major factors that need to be taken into consideration for economic evaluation of a CCHP system are its initial investment, operating and maintenance costs (MCs), fuel price and the price of energy purchased and sold [19]. The daily and annual hours of operation are also critical in determining the cost effectiveness of the CCHP system's installation. The capital costs (CC) of various plant items of the present CCHP system are listed in Table 4.

The thermoeconomic parameters calculated and discussed in this paper are the avoided cost (AC), the total annual saving (AS) and payback period (PP). AC is the savings achieved by producing cooling, heating and power, which is the total income of the CCHP system. The CCHP system requires that a Stirling engine be installed at the facility to generate power and exhaust heat. Therefore, natural gas will need to be purchased to operate the Stirling engine. The total AS is the savings achieved by eliminating the purchase of natural gas, MC and running cost from the AC. AC and the total AS are given by:

$$AC = HP \times \sum Q_h + CP \times \sum Q_c + HWP \times \sum Q_{hw} + EP \times \sum P_c \quad (8)$$

$$AS = AC - NGP \times \sum NGBC - MC - RC \quad (9)$$

Table 4

CC of the plant items of the CCHP system

Capital item	Value (RMB¥ ^a)
Stirling engine	350,000
Double effect absorption chiller	160,000
Cooling tower	5,000
Miscellaneous expenses	65,000
Total cost	580,000

^a 1US\$ = 8.3 RMB¥.

where HP is heat price (RMB¥/MW h), CP is cold price (RMB¥/MW h), HWP is domestic hot water price (RMB¥/t), EP is electricity price (RMB¥/kW h), NGP is natural gas price (RMB¥/N m³), $\sum$ NGBC is annual natural gas burning capacity (N m³/y), MC is maintenance cost and RC is running cost. PP is the ratio of the capital invested to the project annual cash flows in the financial period, which is expressed by the following equation:

$$PP = \frac{\sum \text{capital invested}}{\sum \text{project cash flows in financial period}} = \frac{CC}{AS} \quad (10)$$

On the basis of an electricity price EP of 0.62 RMB¥/kW h and natural gas price NGP 2.1 RMB¥/N m³ in Shanghai, China, as well as the values of COP of the refrigeration cycle and heating cycle of a conventional compression refrigeration plant of 2.5 and 3.2, respectively, the energy prices to be applied in the economic analysis are determined as heat price HP 194 RMB¥/MW h, cold price CP 248 RMB¥/MW h and domestic hot water price HWP 15 RMB¥/MW h. Otherwise, natural gas consumption is calculated per heating value of 10 kW h/N m³, and the MC of the Stirling engine is assumed at the rate of 0.03 RMB¥/kW h. The calculation results of the thermoeconomic analysis of the CCHP system are listed in Table 5.

Table 5 shows a PP for this option of 3.36 years. When compared to similar investigations in other CCHP applications reported by others [20,21], in which PPs of approximately six years were achieved, it appears low. The main reason for this is that this case has a higher plant utilization rate and larger duty than the other applications. Furthermore, supplementary facilities, like a separate conventional gas boiler and motor driven chillers, are not taken into account when calculating CC.

One of the main factors that influences the thermal economy of the CCHP system is the natural gas price. Fig. 2 compares the total ASs and PP of the present CCHP system with respect to different natural gas prices. If the natural gas cost decreases slightly, due to taxes or to a lower market price, a CCHP system will be more profitable. At a price of 1.6 RMB¥/N m³, the total ASs is 271418 RMB¥, and the PP is only 2.14 years. Such a case is applicable in Beijing, China.

Table 5

Cash flow analysis parameters for the present CCHP system with the Stirling engine

Parameters	Calculation expression	Units	Values
Annual power generating income	$PGI = EP \times \sum P_c$	RMB¥	271,560
Annual heating income	$HI = HP \times \sum Q_h$	RMB¥	21,203
Annual refrigeration income	$RI = CP \times \sum Q_c$	RMB¥	50,268
Annual domestic hot water income	$HWI = HWP \times \sum Q_{hw}$	RMB¥	279,252
Annual natural gas cost of Stirling engine	$NGC = NGP \times \sum NGBC$	RMB¥	413,910
Annual MC of Stirling engine	$MC = 0.03 \times \sum P_c$	RMB¥	13,140
Annual running cost of plants	RC	RMB¥	22,365
Annual gross charge	$GC = NGC + MC + RC$	RMB¥	449,415
Annual AC	$AC = PGI + HI + RI + HWI$	RMB¥	622,283
Total ASs	$AS = AC - GC$	RMB¥	172,868
Capital costs	CC	RMB¥	580,000
Payback period	PP	Years	3.36

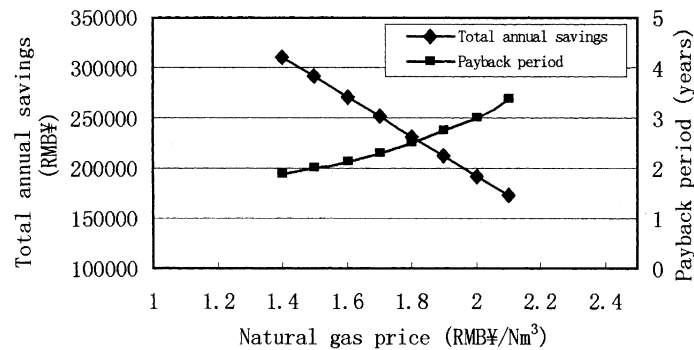


Fig. 2. Variations in the total annual savings and payback period of the present CCHP system with different natural gas prices.

5. Conclusions

The concept of trigeneration is based on the principle of thermal cascading that consists of generating power on site where a substantial fraction of the waste heat produced is recovered to satisfy the heating/cooling demand of the end user. Thus, a considerable enhancement of the overall conversion efficiency can be achieved.

The energy efficiency of the present CCHP system with an available Stirling engine can be expressed by comparing values of the PER for the designed system and for a conventional independent system. According to the calculated values PER and Δq for the designed CCHP system, it is possible to claim that the designed CCHP system with available Stirling engine saves more than 33% of the primary energy compared to a conventional independent system at the required energy flows for the reference energy parameters stated in this paper, which shows a large potential for energy saving in the CCHP system. What's more, the thermal performance of the absorption chiller has a large influence on the CCHP system's energy efficiency.

To evaluate the thermal economics of the CCHP system with Stirling engine, AC, total AS and PP are calculated in this paper, which are functions of the initial investment, operating and MCs, fuel price and price of energy purchased and sold. The price of natural gas is a key factor that determines the thermal economics of the CCHP system. With respect to the price of natural gas, the PPs of the designed CCHP system with Stirling engine are 3.36 and 2.14 years for the other reference energy prices in Shanghai and Beijing, respectively. In addition, how to make full use of the waste heat is very important for energy efficiency and economic feasibility of the CCHP system.

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